Reentry Risk Assessment for Spaceflight Inc Sherpa-LCT1

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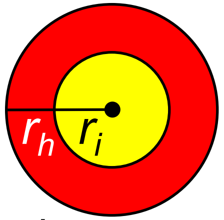
24 February 2022

Reentry Risk Assessment Process

- Casualty risk or **expected casualties (E_C)** depends on:
  - *Size and number of objects that impact the surface*
  - *Human population within geographic debris impact region*
- Method for determining casualty expectation:
  - *Find vehicle **debris area** that survives reentry (survivability analysis)*
    - Depends on component characteristics and flight trajectory
    - “Risky” objects: shielded from heating and/or high melt/ablation temperature
  - *Calculate **casualty area (A_C)** – area of interaction between tumbling debris objects and an average human:*

$$A_C = \sum_{i=1}^{N} \left(\sqrt{\pi r_h^2} + \sqrt{\pi r_i^2} \right)^2$$



r_h = human radius = 0.34 m
r_i = radius for i^{th} object of N total
Applies when kinetic energy > 15 J

  - *Find **population at risk (ρ)** within debris impact region*
    - For random reentry, impact region is bounded by North/South latitudes corresponding to orbital inclination, and population at risk is latitude-weighted
    - Expressed in terms of expected casualties per casualty area
  - *Calculate **expected casualties: $E_C = \rho A_C$***

Modeling Reentry Survivability

- Flight Trajectory
  - *Rigid-body dynamics*
  - *Planet (Earth) dynamics*
  - *Atmosphere model and drag bridging*
  - *Gives velocity, altitude, flight path angle, deceleration*
- Heating Environment
  - *Free-molecular heating and continuum aeroheating*
  - *Transition bridging between free-molecular and continuum regimes*
  - *Gives heat transfer coefficient over the surface*
- Body Response
  - *Transient conduction with re-radiation cooling*
  - *Wall phase change (melting or ablation)*
  - *Gives wall temperature and mass change*

AHaB Reentry Survivability Tool

- AHaB (Atmospheric Heating and Breakup) developed under Aerospace IR&D
- Flight Trajectory Approach
  - *3-DOF rigid-body dynamics*
  - *Oblate, rotating Earth*
  - *4th-degree zonal harmonics*
  - *Martino model for drag bridging*
  - *1976 US Standard Atmosphere*
  - *Can also read pre-defined trajectories*
- Heating Environment Approach
  - *Free-molecular heating*
    - Expression for impact normal to flat plate, with shape factors (based on methods of Cropp and Klett, Sandia)
    - Function of density and velocity ($\propto \rho, V^3$)
  - *Continuum aeroheating*
    - Detra-Kemp-Riddell correlation for stagnation point, with shape factors (based on methods of Cropp and Klett, Sandia)
    - Function of body radius, wall temperature, freestream velocity, freestream density ($\propto 1/\sqrt{R}, \sqrt{\rho}, V^{3.15}$)
  - *Transition bridging*
    - Matting model (NASA) between free-molecular and continuum regimes

AHaB Reentry Survivability Tool

- Heating Environment Approach, cont'd
  - *Additional models available, as needed*
    - Oxidation heating – proper use requires configuration-dependent and time-dependent empirical data
    - Radiative heating using Tauber-Sutton approach for super-orbital airspeeds
- Body Response Approach
  - *Transient conduction*
    - 1-D conduction equation generalized to Cartesian, cylindrical, and spherical coordinates
    - Implicit finite-volume discretization for unconditional numerical stability
    - Flexible boundary conditions (heat flux or temperature, as needed)
  - *Re-radiation cooling*
    - Stefan-Boltzmann law for gray bodies
  - *Wall phase change (melting or ablation)*
    - Wall temperatures will not exceed material melt/ablation temperature
    - Mass removed from external surface according to applied heat of fusion
    - Conduction continues through wall
    - Mass loss ceases if temperature falls below melt/ablation temperature

Survivability Analysis Approach with AHaB

- Initial trajectory:
  - *Spacecraft assumed to be tumbling*
  - *Orbital decay simulated from initial orbit to 120 km altitude (entry interface)*
  - *Survivability analysis initialized at entry interface*
- Component separation and demise (complete mass loss) assumptions:
  - *All components are initially attached to spacecraft*
  - *Demise may occur for either attached or separated components*
  - *Demise or initial melting may release attached components, depending on details of specific attachment configuration*
  - *Components may be thermally shielded by other components*
- Survivability is modeled with AHaB tool, providing:
  - *Sequence of events for reentry breakup*
  - *Debris separation altitudes from parent body*
  - *Debris demise altitudes*
  - *Mass, debris area, and casualty area of surviving debris*

Data Needed for Survivability Analysis

- Detailed analysis approach requires the following:
  1. *A parts list for spacecraft ("parts" includes housing contents, where applicable, e.g., battery cells, reaction wheels, etc.)*
  2. *Masses for each part (e.g., mass statement)*
  3. *Material for each part (e.g., Al 2024, 410 SS, CRES, Ti-6Al-4V, etc.)*
  4. *Physical dimensions for each part (height, width, length, wall thickness, facesheet thickness, honeycomb density, etc.)*
  5. *Briefing charts, schematics, and drawings illustrating shape of each part (charts often suffice)*
  6. *Briefing charts, schematics, and drawings showing placement of parts in relation to each other (charts often suffice)*
  7. *Initial parameters of the disposal orbit (orbital inclination, at a minimum)*
  8. *Expected year of reentry (a.k.a., orbital lifetime)*

Data Sources and Assessment Conditions

- Component and configuration data derived from Spaceflight Inc:
  - *"Sherpa-LTC Summary for Aerospace Corp.pdf," 29 Sep 2021*
  - *"Sherpa-LTC Summary for Aerospace Corp Benchmark.pdf," 28 Jan 2022*
  - *"Sherpa-LTC ODAR Analysis.xlsx," 28 Jan 2022*
  - *"Sherpa-LTC Inputs to Aerospace Corp 20220214.xlsx," 14 Feb 2022*
  - *"RE: [External] - RE: DAS input file for Sherpa-LTC1," 22 Feb 2022, email with data for revised propellant tanks replacing steel alloy with aluminum alloy*
  - *"RE: [External] - RE: DAS input file for Sherpa-LTC1," 24 Feb 2022, email with expected year of reentry*
  - *Point of contact: Eric Lund (elund@spaceflight.com)*

- Assessment conditions:
  - *Reentry in year 2025*
  - *53° orbital inclination, with confirmation to 97.7° (Sun-synchronous) inclination*
  - *Circularization through natural decay simulated to 120 km*
    - Trajectory initial conditions for analysis are those at 120 km
  - *Initial temperature of 300 K at 120 km*

Survivability Results

53° Orbital Inclination

Time (EI+)	Key Events	Demise
1071 sec	88.2 km	CCS & 2-way QuadPack
1100 sec	85.6 km	R2A & 4-way QuadPack
1208 sec	70.6 km	24-inch J-channel spacer ring
1221 sec	68.0 km	CAB hex plate
1255 sec	59.9 km	Aft CAB Bulkhead

Notes	
(light yellow)	Property estimated, or dimension derived from mass
(orange)	Survives and poses risk
(light blue)	Risk negligible or KE < 15 J

Object Description	Shape	Count	Material Type	Diam/Width (m)	Length (m)	Wall/Core Thickness (m)	Face Sheet Thickness (m)	Height or Min Diam (m)	Unit Mass (kg)	Total Mass (kg)	Separation Altitude (km)	Demise Altitude (km)	Debris Area (m^2)	Total Debris Area (m^2)	Total Casualty Area (m^2)
STRUCTURE AND EQUIPMENT															
Upper half of 24-in separation system	Ring	1	Al 6061-T6	0.610	0.031	0.011			1.80	1.80		84.2	0.000	0.000	0.000
24-inch J-channel spacer ring	Ring	1	Al 6061-T6	0.667	0.083	0.011			5.26	5.26		70.7	0.000	0.000	0.000
Solar panel wing	Plate	6	Al 6061-T6	0.546	0.549	0.003		0.060	2.35	14.10		96.0	0.000	0.000	0.000
CAB hex plate	Ring	2	Al 6061-T6	0.822	0.070	0.021			10.00	20.00		68.0	0.000	0.000	0.000
CAB interior wall	Plate	6	Al 6061-T6	0.118	0.318	0.008			0.83	4.98	68.0	67.8	0.000	0.000	0.000
CAB corner brace	Box	6	Al 6061-T6	0.151	0.178	0.004		0.151	1.10	6.60		88.2	0.000	0.000	0.000
Port 4 avionics adapter plate	Plate	1	Al 6061-T6	0.294	0.311	0.005			1.15	1.15		71.9	0.000	0.000	0.000
R2A-Core	Box	1	Al 6061-T6	0.285	0.285	0.005		0.090	3.20	3.20		85.6	0.000	0.000	0.000
NSL black box std	Box	1	Al (generic)	0.054	0.089	0.006		0.047	0.29	0.29		83.0	0.000	0.000	0.000
Camera bracket	Plate	2	Al 6061-T6	0.146	0.178	0.006			0.62	1.24		85.6	0.000	0.000	0.000
IMPERX camera	Box	2	Al 6061-T6	0.037	0.072	0.004		0.037	0.12	0.23		88.2	0.000	0.000	0.000
Camera lens assembly	Cylinder	2	SS 304	0.034	0.047	0.003			0.13	0.27	85.6	73.3	0.000	0.000	0.000
Battery thermal isolator	Plate	2	G10/FR4	0.102	0.145	0.009			0.26	0.52	70.6	68.6	0.000	0.000	0.000
Battery module	Box	2	Al 6061-T6	0.100	0.139	0.018		0.100	2.65	5.30	68.6	58.1	0.000	0.000	0.000
QuadPack adapter plate	Plate	4	Al 6061-T6	0.297	0.311	0.007			1.73	6.91		68.8	0.000	0.000	0.000
Empty 2-way QuadPack	Box	2	Al 6061-T6	0.250	0.440	0.004		0.250	6.30	12.60		88.2	0.000	0.000	0.000
Empty 4-way QuadPack	Box	1	Al 6061-T6	0.250	0.440	0.005		0.250	7.50	7.50		85.6	0.000	0.000	0.000
QuadPack mass model	Box	1	Al 6061-T6	0.250	0.528	0.017		0.250	26.30	26.30	68.0	64.4	0.000	0.000	0.000
RPG base ring	Ring	1	Al 6061-T6	0.626	0.038	0.026			5.08	5.08	68.0	54.8	0.000	0.000	0.000
RPG leg	Box	6	Al 6061-T6	0.051	0.196	0.006		0.051	0.63	3.78	54.8	54.2	0.000	0.000	0.000
RPG triangle plate	Plate	1	Al 6061-T6	0.346	0.400	0.012		0.076	4.47	4.47		69.2	0.000	0.000	0.000
RPG MLB adapter plate	Plate	3	Al 6061-T6	0.255	0.322	0.027			2.43	7.29	54.2	53.2	0.000	0.000	0.000
Lower 8-in separation system	Ring	3	Al 6061-T6	0.118	0.045	0.039			1.19	3.57		53.9	0.000	0.000	0.000
CCS enclosure	Box	1	Al 6061-T6	0.190	0.382	0.004		0.272	4.81	4.81		88.2	0.000	0.000	0.000
Torque rod	Cylinder	3	Iron	0.020	0.300	0.004			0.45	1.35	88.2	67.0	0.000	0.000	0.000
AD avionics	Box	4	Al 6061-T6	0.120	0.150	0.016		0.100	3.00	12.00	88.2	66.1	0.000	0.000	0.000
RWA enclosure	Box	3	Al 6061-T6	0.140	0.150	0.003		0.042	0.57	1.71	88.2	80.6	0.000	0.000	0.000
RWA rotor	Ring	3	SS 410	0.135	0.037	0.003			0.40	1.20	80.6	69.7	0.000	0.000	0.000
PROPULSION															
100504_AFT CAB BULKHEAD	Disk	1	Al 7076-T6	0.572		0.025			3.32	3.32	70.6	59.9	0.000	0.000	0.000
100602_DMLS PRESSURANT TANK_POLARIS 100417 CONFIG	Cylinder	2	Ti-6Al-4V	0.085	0.327	0.003			0.98	1.96	59.9	0.0	0.028	0.056	1.176
100535_OX TANK ASSEMBLIES	Cylinder	3	Al 6061-T6	0.204	0.340	0.004			4.75	14.25		64.1	0.000	0.000	0.000
FLUID COMPONENTS, TOP HALF	Cylinder	1	SS 316	0.025	0.416	0.0125			3.27	3.27		62.3	0.000	0.000	0.000
100733_FUEL TANK ASSEMBLY	Cylinder	1	Al 6061-T6	0.204	0.340	0.004			4.75	4.75		88.2	0.000	0.000	0.000
100719_A LEG, THRUST DECK	Beam	3	Al 7076-T6	0.015	0.243	0.004		0.015	0.22	0.66		89.6	0.000	0.000	0.000
FLUID COMPONENTS, BOTTOM HALF	Cylinder	1	SS 316	0.025	0.387	0.0125			3.60	3.60		74.0	0.000	0.000	0.000
100716_THRUST BULKHEAD, POLARIS	Ring	1	Al 7076-T6	0.446	0.013	0.021			1.03	1.03		82.8	0.000	0.000	0.000
100688_OCELOT ENGINE ASSEMBLIES	Cylinder	4	Niobium-C103	0.086	0.202				0.51	2.04	82.8	0.0	0.017	0.069	2.141
Totals		88								154.34				0.1	3.32

88.6 kg were part of analyzed configuration but not part of Sherpa-LTC2

RWA rotors

Titanium tanks

Fluid comps, top

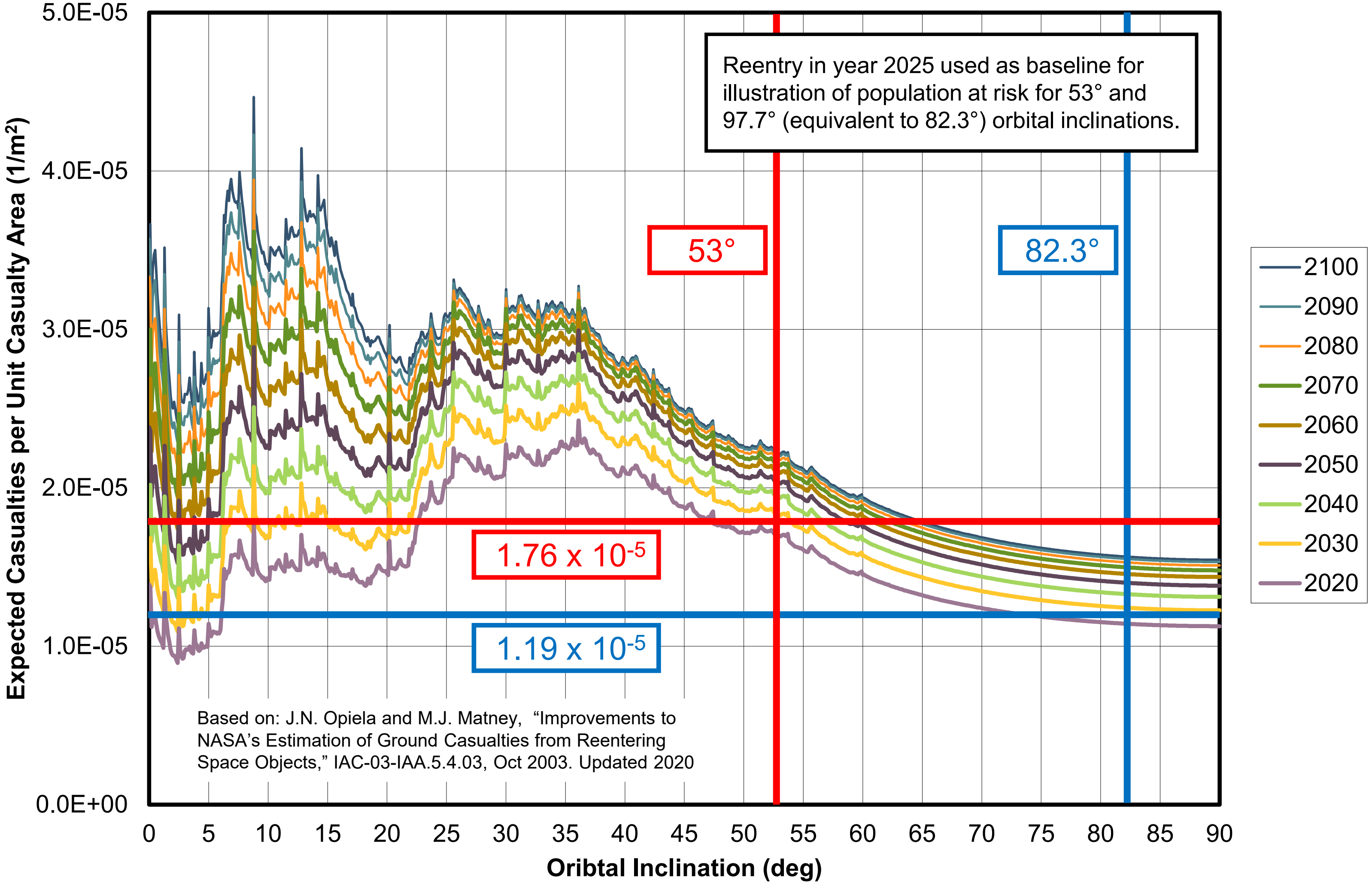
Fluid comps, bottom

Ocelot engines

Casualty Area

		53° Inclination		97.7° Inclination	
Object Name	Material	Part Count	Casualty Area (m^2)	Part Count	Casualty Area (m^2)
Pressurant Tank	Ti-6Al-4V	2	1.176	2	1.176
Engine	Niobium-C103	4	2.141	4	2.141
TOTAL		**6**	**3.32**	**6**	**3.32**

Population at Risk



Expected Casualties

- For reentry in year 2025, predicted expected casualties for 53° inclination are:

$$(3.32\ m^2) \times (1.76 \times 10^{-5}\ m^{-2}) = 0.6 \times 10^{-4}$$

- For reentry in year 2025, predicted expected casualties for 97.7° inclination are:

$$(3.32\ m^2) \times (1.19 \times 10^{-5}\ m^{-2}) = 0.4 \times 10^{-4}$$

- US Government Orbital Debris Mitigation Standard Practices (ODMSP) specify that expected casualties from reentry be less than 1×10^{-4}

- Notes on reported results:
  - *Items denoted as "Risk negligible or KE < 15 J" are either made from materials with no risk of surviving or have less than 15 J of kinetic energy at ground impact, or both, and do not pose a casualty risk*
  - *Results are subject to revision based on receipt of additional and/or modified data*

- On the next chart, expected casualties are parameterized for future years over the orbital-inclination range of interest

Expected Casualties